Sampled Adaptive Control for Multi-joint Robotic Manipulator with Force Uncertainties

Hao Zhou, Hongbin Ma(✉), Haiyang Zhan, Yimeng Lei, and Mengyin Fu

School of Automation, Beijing Institute of Technology,
Beijing 100081, People's Republic of China
mathmhb@qq.com

Abstract. This paper addresses force estimation and trajectory tracking control for robotic manipulator in the presence of uncertain external load force at end effector. One-step Guess method using one step history data sampled from actual continuous-time plant at a constant sampling interval is developed to estimate the unknown fixed or time-varying force. A discrete-time adaptive controller based on estimation of load force is designed to track desired joint trajectory. System simulation of a 6 DOF manipulator is carried out with the help of robotic toolbox in MATLAB, which demonstrates performances of the proposed scheme dealing with both fixed and variable forces, compared with traditional control method.

Keywords: Robotic manipulator · Force estimation · Adaptive control · One-step guess

1 Introduction

Nowadays intelligent robots have come into our daily life as well as industrial process. The fact that robots do repeated work and deal with single kind of problem can not meet the increasing demand of robotic intelligence any more. On the one hand, in modern factory robotic arms are supposed to face uncertain tasks such as assembling or carrying some objects with unknown weight or even time-varying weight. On the other hand, smart robots need to possess excellent perception in unknown outside environments, for example, sense of external force or weight without force sensor in order to make optimal decisions. Therefore those motivate us to settle estimation of external force and position tracking control for robotic manipulator in the presence of uncertain load force at its end effector.

Position tracking of robotic manipulator always seems to be a fundamental and difficult task in robot control, especially in the presence of external disturbances and modal uncertainties. Various kinds of control methods have been used to address this problem, including proportional plus derivative (PD) control [8], iterative learning scheme [5], sliding PID control [12], repetitive and adaptive motion control [4].

This work is partially supported by National Natural Science Foundation (NSFC) under Grant 61473038.

N. Kubota et al. (Eds.): ICIRA 2016, Part I, LNAI 9834, pp. 14–25, 2016.
DOI: 10.1007/978-3-319-43506-0_2

To achieve high precise tracking of robot with load uncertainties, robust control that can reject load uncertainties have been studied extensively in literatures. A input-output robust control design, which could guarantee tracking performance in the presence of load variation as well as other disturbances was firstly introduced in [13]. A benchmark problem for robust feedback control for a flexible manipulator was presented in [11]. The robust control problem of robot manipulators could be translated into a optimal control [7] where load uncertainties were first reflected in the performance index and this approach was illustrated with two-joint SCARA type robot. Adaptive control has great advantages in coping with uncertainties. In [10], an adaptive control scheme was proposed for rigid link robots, where control signal computations were performed continuously and the control coefficient computations are performed in discrete time. An adaptive control system, requiring calculating only one parameter the tip load, was designed in [3]. Force estimation is important for adaptive control of robotic manipulators with unknown load at end effector, since usually it constitutes one part of control torque. Besides, high precise estimation of force can replace force sensor with high cost in application of intelligent robot. An approach, providing force estimation as well as full state estimation in the presence of robot inertial parameter variations and measurement noise, was proposed in [1]. Some intelligent control methods have also been adopted such as artificial neural networks (ANN) [14] and switched adaptive control [15,16].

Among the existing control methods, discrete-time adaptive control methods for robotic manipulators with unknown load force at end effector, are still seldom concerned. During the past decades, we have witnessed extensive application of digital computers in control system due to availability of cheap chip and the advantages of digital signals over continuous signals. The practical implementation of theoretic control methods will benefit much from directly taking true plant as sampled system and then designing control scheme in view of discrete-time control system, such as testing real-time performance easily. However, it is difficult to design a satisfactory discrete-time control scheme for robotic system. Force estimation only using history information of joint angles and velocities is also seldom studied because of the modal complexities of robotic system. Since multi-joint will increase modeling and computation difficulties, robotic manipulators used for simulation in many previous literatures only have one or two links while many a manipulator of six degrees of freedom (DOF) or more could be seen in practice, especially in intelligent robot field.

Our study object is robotic manipulator with unknown external load force at end effector, the only uncertainty considered in this paper for simplicities. Discrete-time adaptive control method based on One-step Guess (OSG) [9] was first introduced for load uncertainties [6], and this paper extend this method to a general case. Mathematically external force timed by Jacobian matrix is added to robotic dynamic equation, instead of direct addition as in some literatures. Force estimation is obtained through OSG, by which the discrete-time adaptive controller can cope with position tracking. The performance of this scheme is demonstrated with simulations for PUMA560, a kind of 6 DOF manipulator, further than the work in [6]. Robotic toolbox (RVC) [2] in MATLAB contributes to dynamic calculations and simulations. This scheme has three main advantages: free of force sensor, convenience for digital implementation, high-precision tracking.

The remaining part of this paper is organized as follows. First, Sect. 2 introduces the dynamics of robotic manipulator with external load force and the problem to be studied. Section 3 presents the detailed design of discrete-time force estimation and adaptive controller and briefly analyzes convergence characteristics of trajectory errors. Then Sect. 4 illustrates the simulation results of a 6 DOF manipulator with OSG-based adaptive controller and force estimation. Finally Sect. 5 briefly summarizes our work and also presents the future work.

2 Problem Formation

The dynamic model of a serial robotic manipulator in the presence of load force at its end effector can be represented by the following equation in matrix form

$$M(q)\ddot{q} + C(q, \dot{q}) + G(q) = u + J^T f \tag{1}$$

where n is the degree of freedom, $q \in R^n, \dot{q} \in R^n, \ddot{q} \in R^n$ are respectively the vector of generalized joint coordinates, velocities and accelerations, $M(q) \in R^{n\times n}$ is the joint-space inertial matrix, $C(q, \dot{q}) \in R^{n\times n}$ is the Coriolis and centripetal coupling matrix, $G(q) \in R^n$ is the gravity loading, and $u \in R^n$ is the vector of generalized actuator forces associated with the generalized coordinates q. The last term gives the joint forces due to external payload f applied at the end effector and J is the manipulator Jacobian matrix.

As is well known, the manipulator Jacobian transforms joint velocity to an end effector spatial velocity and the Jacobian transpose transforms a wrench applied at the end effector to torques experienced at the joints. It is noted that both of two transforms hold respectively in the same coordinate frame, either both in the world coordinate frame or both in the end effector coordinate frame. Generally speaking, the world coordinate frame is adopted and hence we have the following relationship

$$u_d = J^T(q)f \tag{2}$$

where the elements of u_d are joint torques for revolute joints. Generalized force f is denoted by $f = [f_x\ f_y\ f_z\ T_x\ T_y\ T_z]^T$, that is, f can represent an arbitrary external force or torque applied at end effector in all possible directions. For example, $f = [f_x\ f_y\ 0\ 0\ 0\ 0]^T$ represents a horizontal force.

In practice, the external force f in the above Eq. (1) is not always known in advance, which results in bad performance of some traditional methods such as PD feedforward control, especially in the case of large value or time-varying case. The ultimate goal of control system is to achieve trajectory tracking, which needs control system to estimate f using observed history information such as sampled joint angle values and velocities. Before designing computation methods of force estimation and control torque, system discretization should be first done since digital control system is widely used. Then we estimate the load force at past time and assume that the force vary small in the next sampling time which corresponds with most actual cases since generally speaking sampling interval is very small. By taking force estimation at the last time as current time force, we can design the adaptive controller to finish trajectory tracking.

3 Design of Estimation and Controller

In this section, we design force estimation and tracking controller for the above problem, mainly consisting of the following four parts:

1. Discretization of manipulator dynamic equation;
2. Designing estimation algorithm of external force based on sampled history information consisting of joint angle values and velocities;
3. Designing control signal at the current time according to estimation of force of last time instant;
4. Analyzing convergence characteristics of trajectory error.

3.1 Discretization of Dynamic Equation

First let $\bar{q} = [q \quad \dot{q}]^T$, $q \in R^n$ and $M(q)$ is usually invertible, then Eq. (1) can be rewritten in the following state space form

$$\dot{\bar{q}} = A(q, \dot{q})\bar{q} + B(q)u + F(q)f - Q(q)G(q) \tag{3}$$

where

$$\begin{aligned} A(q, \dot{q}) &= \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ 0_{n\times n} & -M^{-1}(q)C(q, \dot{q}) \end{bmatrix} \\ B(q) = Q(q) &= \begin{bmatrix} 0_{n\times n} \\ M^{-1}(q) \end{bmatrix} \\ F(q) &= \begin{bmatrix} 0_{n\times n} \\ M^{-1}(q)J^T(q) \end{bmatrix} \end{aligned} \tag{4}$$

The sampling period is denoted as T and then at time $t = (k-1)T$ the joint angle value and velocity are respectively $x_k = q(t_k)$ and $\dot{x}_k = \dot{q}(t_k)$. Let the space state of discrete-time system be $\bar{x}_k = [x_k \quad \dot{x}_k]^T$, then from theory of discretization we can get

$$\begin{aligned} L_k &= e^{A(q(t_k), \dot{q}(t_k))T} \\ H_k &= \int_{(k-1)T}^{kT} e^{A(q,\dot{q})t} B(q)dt \\ R_k &= \int_{(k-1)T}^{kT} e^{A(q,\dot{q})t} F(q)dt \\ S_k &= \int_{(k-1)T}^{kT} e^{A(q,\dot{q})t} Q(q)dt \end{aligned} \tag{5}$$

where L_k, H_k, R_k and S_k are counter-part matrices corresponding to the continuous time matrices $A(q,\dot{q})$, $B(q)$, $F(q)$ and $Q(q)$ in the Eq. (3). Hence the discrete-time space state equation for robotic manipulator is as follows

$$\bar{x}_{k+1} = L_k\bar{x}_k + H_k u_k + R_k f_k - S_k G(x_k) \tag{6}$$

Since only the sampled values $x_k = q(t_k)$ and $\dot{x}_k = \dot{q}(t_k)$ at the sampling time instant t_k can be obtained as well as history values, the exact values of L_k, H_k, R_k and S_k can not be calculated using Eq. (5). Instead, we can use the following formula:

$$\begin{aligned}
\hat{L}_k &= e^{A_k T} \\
\hat{H}_k &= \int_{(k-1)T}^{kT} e^{A_k t} B(x_k) dt \\
\hat{R}_k &= \int_{(k-1)T}^{kT} e^{A_k t} F(x_k) dt \\
\hat{S}_k &= \int_{(k-1)T}^{kT} e^{A_k t} Q(x_k) dt
\end{aligned} \tag{7}$$

where $A_k = A(x_k, \dot{x}_k)$, which is determined at each sampling time. As a result, L_k, H_k, R_k and S_k can be calculated through Runge-Kutta method or other numerical integral methods. The estimated errors can be denoted as:

$$\begin{aligned}
&\tilde{H}_k = H_k - \hat{H}_k,\ \tilde{L}_k = L_k - \hat{L}_k \\
&\tilde{R}_k = R_k - \hat{R}_k,\ \tilde{S}_k = S_k - \hat{S}_k
\end{aligned} \tag{8}$$

which will generate modal calculation errors but can be small enough if the sampling period is small enough.

3.2 Force Estimation

From Eq. (6), at time $t_{k-1} = (k-1)T$, we have

$$\bar{x}_{k-1} = L_{k-1}\bar{x}_{k-1} + H_{k-1}u_{k-1} + R_{k-1}f_{k-1} - S_{k-1}G(x_{k-1}) \tag{9}$$

Then

$$R_{k-1}f_{k-1} = \bar{x}_{k-1} - L_{k-1}\bar{x}_{k-1} - H_{k-1}u_{k-1} + S_{k-1}G(x_{k-1}) \tag{10}$$

which can be taken as the constraint equation of f_{k-1}. Then we denote the right hand side of Eq. (10) by $P(\bar{x}_k, \bar{x}_{k-1})$, that is,

$$P(\bar{x}_k, \bar{x}_{k-1}) = \bar{x}_{k-1} - L_{k-1}\bar{x}_{k-1} - H_{k-1}u_{k-1} + S_{k-1}G(x_{k-1}) \tag{11}$$

The constraint Eq. (10) is equivalent to

$$R_{k-1}f_{k-1} = P(\bar{x}_k, \bar{x}_{k-1}) \tag{12}$$

Generally R_{k-1} is not a square matrix and thus not invertible. Hence we could adopt the least-square method or regularized least-square method to solve the above Eq. (12). Besides, as previously mentioned, only estimation values $\hat{L}_{k-1}$, $\hat{H}_{k-1}$, $\hat{R}_{k-1}$ and $\hat{S}_{k-1}$ could be used at time t_k. Based on the two points, force estimation of f_{k-1} can be given as follows

$$\hat{f}_{k-1} = (\hat{R}_{k-1}^T \hat{R}_{k-1} + Q_{\mathrm{f}}^T Q_{\mathrm{f}})^{-1} \hat{R}_{k-1}^T \hat{P}(\bar{x}_k, \bar{x}_{k-1}) \tag{13}$$

where

$$\hat{P}(\bar{x}_k, \bar{x}_{k-1}) = \bar{v}_k - \hat{L}_{k-1}\bar{v}_{k-1} - \hat{H}_{k-1}u_{k-1} + \hat{S}_{k-1}G(v_{k-1}) \tag{14}$$

and Q_{f} is a matrix for fine-tuning the estimation such that $Q_{\mathrm{f}}\hat{f}_{k-1} = 0$, which can reflect a prior knowledge on the unknown force.

Since the change of external force during one sampling interval is assumed to be very small, hence estimated value $\hat{f}_{k-1}$ can serve as a priori estimation of f_k for designing control signal u_k, that is,

$$\check{f}_k = \hat{f}_{k-1} = (\hat{R}_{k-1}^T \hat{R}_{k-1} + Q_{\mathrm{f}}^T Q_{\mathrm{f}})^{-1} \hat{R}_{k-1}^T \hat{P}(\bar{x}_k, \bar{x}_{k-1}) \tag{15}$$

although the unknown force f_k is unavailable at sampling time $t_k = kT$.

3.3 Adaptive Controller Design

The idea of adaptive controller (indirect approach) consists in replacing the unknown parameter by its estimation. After obtaining a prior estimation of f_k, we can design the controller for the Eq. (6) from which the following equation can be obtained

$$H_k u_k = \bar{x}_{k+1} - L_k \bar{x}_k - R_k f_k + S_k G(x_k) \tag{16}$$

Denote the desired reference trajectory of joint vector at sampling time t_{k+1} by $\bar{x}_{k+1}^*$. The actual joint vector is $\bar{x}_k$ at time t_k. The ideal control signal u_k can lead to the result that $\bar{x}_{k+1} = \bar{x}_{k+1}^*$. The right hand side of Eq. (16) can set as

$$V(\bar{x}_{k+1}, \bar{x}_k) = \bar{x}_{k+1} - L_k \bar{x}_k - R_k f_k + S_k G(x_k) \tag{17}$$

Likewise, only the estimation values at time t_k can be used then the following equation

$$\hat{V}(\bar{x}_{k+1}, \bar{x}_k^*) = \bar{x}_{k+1}^* - \hat{L}_k \bar{x}_k - \hat{R}_k f_k + \hat{S}_k G(x_k) \tag{18}$$

is estimation of $V(\bar{x}_{k+1}, \bar{x}_k)$.

In order to track the desired reference trajectory at time $t_{k+1} = (k+1)T$, in other words, $\bar{x}_{k+1} = \bar{x}_{k+1}^*$, the control signal at time $t_k = kT$ should be the following regularized least-square form

$$u_k = (\hat{H}_k^T \hat{H}_k + Q_u^T Q_u)^{-1} \hat{H}_k^T \hat{V}(\bar{x}_{k+1}, \bar{x}_k^*) \tag{19}$$

where Q_u is a matrix for fine-tuning the components of vector u_k, which might improve the performance of control. This controller is based on One-step Guess method which estimates unknown force using only the information of last time instant and hence results in fast adaption.

3.4 Tracking Characteristics

The Eq. (10) is rewritten as

$$R_{k-1}f_{k-1} = \bar{x}_{k-1} - L_{k-1}\bar{x}_{k-1} - H_{k-1}u_{k-1} + S_{k-1}G(x_{k-1}) \tag{20}$$

which can obtain the ideal estimation of force. However, we use the following equation to estimate f

$$\hat{R}_{k-1}\hat{f}_{k-1} = \bar{x}_{k-1} - \hat{L}_{k-1}\bar{x}_{k-1} - \hat{H}_{k-1}u_{k-1} + \hat{S}_{k-1}G(x_{k-1}) \tag{21}$$

From the above Eqs. (20) and (21), we get

$$R_{k-1}f_{k-1} - \hat{R}_{k-1}\hat{f}_{k-1} = -\tilde{L}_{k-1}\bar{x}_{k-1} - \tilde{H}_{k-1}u_{k-1} + \tilde{S}_{k-1}G(x_{k-1}) \tag{22}$$

The actual space state equation and desired equation are respectively

$$\bar{x}_{k+1} = L_k\bar{x}_k + H_k u_k + R_k f_k - S_k G(x_k) \tag{23}$$

and

$$\bar{x}^*_{k+1} = \hat{L}_k\bar{x}_k + \hat{H}_k u_k + \hat{R}_k\hat{f}_{k-1} - \hat{S}_k G(x_k) \tag{24}$$

By subtracting Eq. (24) from Eq. (23), we obtain

$$\bar{x}_{k+1} - \bar{x}^*_{k+1} = \tilde{L}_k\bar{x}_k + \tilde{H}_k u_k + R_k f_k - \hat{R}_k\hat{f}_{k-1} - \tilde{S}_k G(x_k) \tag{25}$$

where $\tilde{H}_k = H_k - \hat{H}_k,\ \tilde{L}_k = L_k - \hat{L}_k,\ \tilde{R}_k = R_k - \hat{R}_k, \tilde{S}_k = S_k - \hat{S}_k$.

For time instant $t = (k-1)T$, we obtain

$$\begin{aligned}\bar{x}_k - \bar{x}^*_k =& \tilde{L}_{k-1}\bar{x}_{k-1} + \tilde{H}_{k-1}u_{k-1} + \\ & R_{k-1}f_{k-1} - \hat{R}_{k-1}\hat{f}_{k-2} - \tilde{S}_{k-1}G(x_{k-1})\end{aligned} \tag{26}$$

By substituting Eq. (22) into Eq. (26), we get

$$\begin{aligned}\bar{x}_k - \bar{x}^*_k &= \hat{R}_{k-1}\hat{f}_{k-1} - R_{k-1}f_{k-1} + R_{k-1}f_{k-1} - \hat{R}_{k-1}\hat{f}_{k-2} \\ &= \hat{R}_{k-1}(\hat{f}_{k-1} - \hat{f}_{k-2})\end{aligned} \tag{27}$$

From the above Eq. (27), we can conclude that the position trajectory error $\|\bar{x}_k - \bar{x}^*_k\|$ will converge to zero if $\|\hat{f}_{k-1} - \hat{f}_{k-2}\| \to 0$, which can be easily achieved by estimation Eq. (13).

4 Simulation Examples

This section validates the above proposed controller with dynamic simulation, carried out in MATLAB with the help of RVC, a toolbox dealing with robotics and machine vision. As a comparison, the simulation results using PD feedforward controller are also illustrated in this section. In this paper, the plant is PUMA560, a well-known 6 DOF industrial robotic manipulator with unknown load force at the end effector, which results in uncertainties in this robot control system. This manipulator depicted in Fig. 1 has six revolute joints, that is, $n = 6$.

If we are more interested in estimation of external force, then we might use some *a prior* knowledge to set Q_{f} so that we can get more precise estimation. The whole simulation system consists of a continuous-time robotic plant and a discrete-time controller, either PD feedforward one or OSG-based adaptive controller one. The OSG-based adaptive controller is given by the Eq. (19), while the generic PD feedforward controller is given by

$$U_{\mathrm{ff}} = M^*(q^*)\ddot{q}^* + C(q^*, q^*)\dot{q}^* + G(q^*) + \{K_v(\dot{q}^* - \dot{q}) + K_p(q^* - q)\} \tag{28}$$

where q^* and $\dot{q}^*$ are respectively desired joint angle and velocity, and K_v and K_p are velocity and position gain (or damping) matrices respectively. Before adding external force at the end effector, the control gain $K_v = 100 * I_{6\times6}$ and $K_p = I_{6\times6}$ of PD feedforward controller have been well adjusted in order that original control parameters can guarantee a satisfactory result of position trajectory. In this way, we can compare the two kinds of controller in dealing with unknown load force. The sampling time interval is $T = 0.02\,\mathrm{s}$ and the default unit of f is Newton (N).

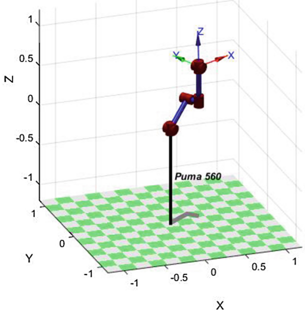
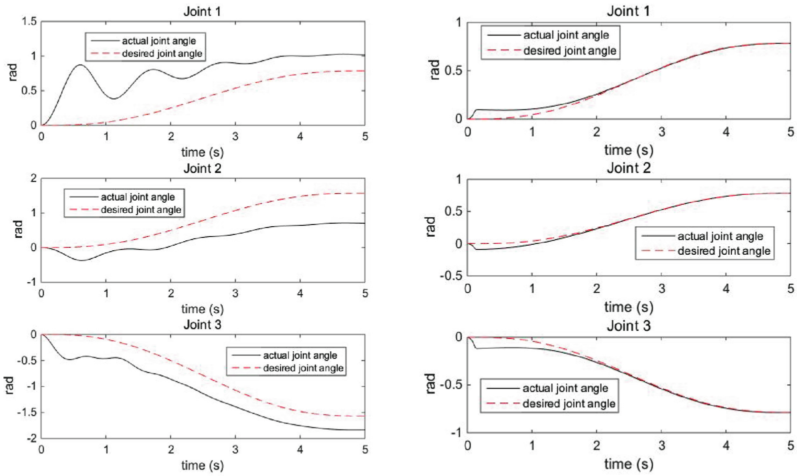


Fig. 1. PUMA560 in MATLAB using RVC

4.1 Fixed Case

The load force applied at the end effector is unknown and fixed, for example, a constant external force $f = [50\ 100\ 0\ 0\ 0\ 0]^T$ N that is a fixed horizon force. We obtain the response curves of PD feedforward control in Fig. 2(a) and OSG-based adaptive controller in Fig. 2(b). The trajectories of joint 4 to joint 6 are not presented in Fig. 2 since they are tracked well both in these two controllers. From these two figures, we can see that the tracking errors in OSG-based adaptive controller converge to zero while the errors of the first joint to the third joint in PD forward control scheme are far from zero.



(a) PD feedforward control (b) OSG-based adaptive control

Fig. 2. Position trajectory results in fixed case

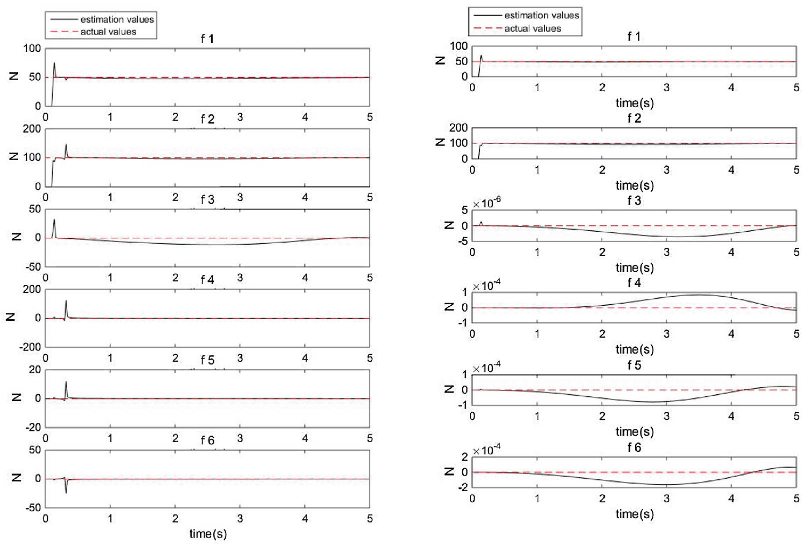


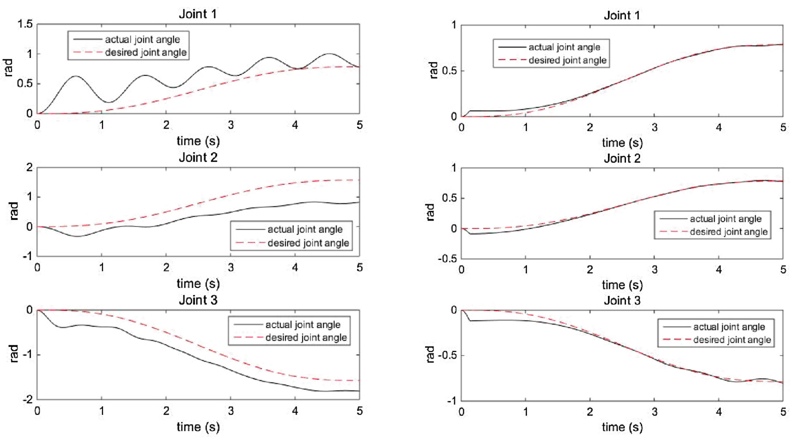
Fig. 3. Force estimation in fixed case

Also the estimation curve of load force is depicted in Fig. 3(a), where each subfigure, from f_1 to f_6, represents one component of force f. We set $Q_{\mathrm{f}} = 0_{6\times 6}$ of Eq. (13) in this simulation. The estimation result of f_3 during tracking is as not good as the other components of load force, which might be a result of singularity of $\hat{R}_{k-1}$ in Eq. (12). However, this estimation deviation has little impact on tracking precision of all joints.

A prior knowledges of direction of load force can be used and in the case of $f = [50\ 100\ 0\ 0\ 0\ 0]^T$, we set $Q_{\mathrm{f}} = \mathrm{diag}\{0, 0, 10, 10, 10, 10\}$. Then estimation curves of load force are illustrated in Fig. 3(b), better than Fig. 3(a).

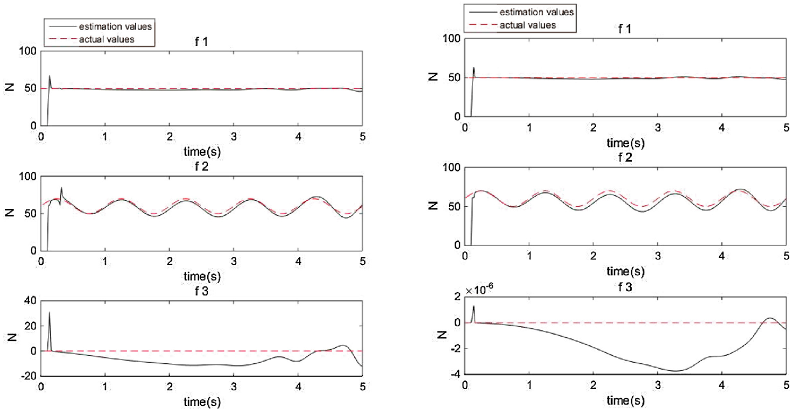
4.2 Time-Varying Case

In practice, external load force might be time-varying and unknown, for example, $f = [50,\ 60{+}10\sin(2\pi t),\ 0,\ 0,\ 0,\ 0]^T$. The tracking trajectories are illustrated in Fig. 4, from which we conclude that OSG-based adaptive control can also deal with time-varying load force well despite of the presence of small estimation deviations of force. The trajectories of joint 4 to joint 6 are not presented in Fig. 4 due to the same reason. The estimation curve of load force is depicted in Fig. 5(a), where only the estimations of f_1 to f_3 are depicted here. Likewise, *a prior* knowledge of the direction of force can be used and the estimation curves of force are depicted in Fig. 5(b) reflecting better estimation with *a prior* knowledge.



(a) PD feedforward control (b) OSG-based adaptive control

Fig. 4. Position trajectory in time-varying case



(a) Without *a prior* knowledge (b) With *a prior* knowledge

Fig. 5. Force estimation in time-varing case

5 Conclusion

In this paper, we have presented a novel scheme of discrete-time force estimation and tracking control based on one-step-guess for robotic manipulator with unknown load force applied at end effector. The history information of joint angle values and velocities sampled from the true arm system is used to estimate the unknown fixed or time-varying force, and a discrete-time adaptive controller based on force estimation is designed to achieve position tracking. Dynamic simulations for a 6 DOF robot manipulator are carried out in MATLAB with RVC toolbox. Simulation results have demonstrated that this control approach could obtain a remarkable tracking performance compared with tradition control scheme. In addition, the estimation method of unknown force also has a considerably high precision, which could be used for intelligent robotic sense of external force.

While the performance of OSG-based adaptive controller has been validated through computer simulation, complete theoretical proof and experimental verification of physical system are also required which will be the goal of the future work. Meanwhile, the proposed scheme mainly considers the uncertainties from external load force. However, a true robotic system also suffers from other disturbances such as friction disturbance, which could result in bad performance. A further development of the control scheme is to study how OSG-based adaptive controller deal with friction disturbance as well as unknown external force.

References

1. Chan, L.P., Naghdy, F., Stirling, D.: Extended active observer for force estimation and disturbance rejection of robotic manipulators. Robot. Auton. Syst. **61**(12), 1277–1287 (2013)
2. Corke, P.: Robotics, Vision and Control. Springer, Heidelberg (2011)
3. Feliu, J.J., Feliu, V., Cerrada, C.: Load adaptive control of single-link flexible arms based on a new modeling technique. IEEE Trans. Robot. Autom. **15**(5), 793–804 (1999)
4. Kaneko, K., Horowitz, R.: Repetitive and adaptive control of robot manipulators with velocity estimation. IEEE Trans. Robot. Autom. **13**(2), 204–217 (1997)
5. Kuc, T.Y., Nam, K.H., Lee, J.S.: An iterative learning control of robot manipulators. IEEE Trans. Robot. Autom. **7**(6), 835–842 (1991)
6. Li, J.P., Ma, H.B., Yang, C.G., Fu, M.Y.: Discrete-time adaptive control of robot manipulator with payload uncertainties. In: IEEE International Conference on Cyber-Technology in Automation, Control and Intelligent Systems, Shenyang, pp. 8–12, June 2015
7. Lin, F., Brandt, R.D.: An optimal control approach to robust control of robot manipulators. IEEE Trans. Robot. Autom. **14**(1), 69–77 (1998)
8. Lozano, R., Valera, A., Albertos, P., Albertos, P., Nakayama, T.: PD control of robot manipulators with joint flexibility, actuators dynamics and friction. Automatica **35**(10), 1697–1700 (1999)
9. Ma, H.B., Rong, L.H., Wang, M.L., Fu, M.Y.: Adaptive tracking with one-step-guess estimator and its variants. In: Proceedings of the 2011 30th Chinese Control Conference (CCC 2011), Yantai, pp. 2521–2526, July 2011
10. Middleton, R.H.: Adaptive control for robot manipulators using discrete time identification. IEEE Trans. Autom. Control **35**(5), 633–637 (1990)
11. Moberg, S., Ohr, J., Gunnarsson, S.: A benchmark problem for robust feedback control of a flexible manipulator. IEEE Trans. Control Syst. Technol. **17**(6), 1398–1405 (2009)
12. Parra-Vega, V., Hirzinger, G., Liu, Y.H.: Dynamic sliding pid control for tracking of robot manipulators: theory and experiments. IEEE Trans. Robot. Autom. **19**(6), 967–976 (2003)
13. Qu, Z.H.: Input-output robust tracking control design for flexible joint robots. IEEE Trans. Autom. Control **40**(1), 78–83 (1995)
14. Teixeira, R.A., Braga, A.D., De Menezes, B.R.: Control of a robotic manipulator using artificial neural networks with on-line adaptation. Neural Process. Lett. **12**(1), 19–31 (2000)
15. Wang, X., Niu, R., Chen, C., Zhao, J.: Switched adaptive control for a classof robot manipulators. Trans. Inst. Measur. Control **36**(3), 347–353 (2014)
16. Wang, X., Zhao, J.: Switched adaptive tracking control of robot manipulators with friction and changing loads. Int. J. Syst. Sci. **16**(6), 955–965 (2015)

http://www.springer.com/978-3-319-43505-3

Intelligent Robotics and Applications
9th International Conference, ICIRA 2016, Tokyo, Japan,
August 22-24, 2016, Proceedings, Part I
Kubota, N.; Kazuo, K.; Liu, H.; Obo, T. (Eds.)
2016, XXIII, 801 p. 555 illus., Softcover
ISBN: 978-3-319-43505-3